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The Effects of the Accuracy of Atmospheric Data on the Structural Design Loads of a Typical Launch Vehicle

20 APRIL 1964

Prepared by
J. S. FIELD and D. E. HARGIS

Prepared for COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

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ABSTRACT

This report documents the effects of simulated inaccuracies of meteorological data on the structural loads of two types of launch vehicles. The effects of inaccuracies ranging from + 10% to - 10% of atmospheric density, atmospheric temperature, windspeed, wind shear and wind shear length were studied. The two launch vehicles used were a liquid propellant boosted vehicle and a relatively small solid propellant boosted vehicle.

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Report No.
TDR-269(4304)-6

THE EFFECTS OF THE ACCURACY OF ATMOSPHERIC DATA ON THE STRUCTURAL DESIGN LOADS OF A TYPICAL LAUNCH VEHICLE

This technical documentary report has been reviewed and is approved for publication and dissemination. The conclusions and findings contained herein do not necessarily represent an official Air Force position.

For Space Systems Division
Air Force Systems Command:

Major J.E. Bekius, SSOW
SSD Staff Meteorologist

For Aerospace Corporation:

W. F. Radcliffe
Associate Director
Engineering Sciences Subdivision

AEROSPACE CORPORATION
El Segundo, California

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FIGURES (Continued)

TABLE

I. INTRODUCTION

A perturbation analysis has been conducted on certain standard atmospheric parameters to determine the effects of errors in measurement on the structural design loads of a launch vehicle. The nominal atmosphere and basic wind profiles used as standard data in this report were obtained from the U.S. Standard Atmosphere 1962 and the USAF Climatic Center Project 4501 report, MMRBM Design Climatology, dated 12 April 1963.

The procedure consisted of first determining a critical altitude and wind direction by flying several trajectories using a nominal atmosphere and various basic wind profiles. Having thus established the critical altitude and wind direction, other trajectories were flown for basic 1%, 5%, and 10% risk wind profiles taken from the Project 4501 report. The effect of errors in measurement of atmospheric data were determined by dispersing individual parameters from the basic 5% risk wind profile. The parameters dispersed were air density, air temperature, wind velocity, wind shear, and wind shear length. The parameters were dispersed ±5% and ±10% from the nominal values. Smooth curves were faired in between these points.

Curves are presented showing the percentage changes in equivalent axial load and bending moments due to individual dispersions. Curves yielding the change in launch risk versus the various dispersions are also presented.

II. SUMMARY

Table 1 presents the detailed effects of +10% dispersions (simulated inaccuracies) in atmospheric data on dynamic pressure, angle-of-attack, bending moment, and launch risk. The effects presented are typical in a qualitative sense for other percentage dispersions.

Effects on q (Dynamic Pressure)

A large deviation in q for both the liquid and solid type vehicles is due solely to dispersed air density. All other dispersed measured data show negligible changes in q.

Effects on α (Angle of Attack)

The large deviations in α are due to dispersions in wind velocity for the liquid vehicle and wind shear for the solid vehicle. All other atmospheric data dispersions result in smaller deviations in α for both vehicles with air temperature dispersions showing negligible deviations in α.

Effects on Bending Moment

The bending moment is a direct function of dynamic pressure and angle of attack; therefore it reflects the combined effect of q and α. From Table 1 it is seen that the greatest deviations in bending moment for the liquid vehicle are due to air density dispersions, because of the large q influence, and wind velocity dispersions, because of the large α influence.

The greatest deviations in bending moment for the solid vehicle (Table 1) are due to air density dispersions, because of the large q influence and wind shear dispersions due to the large α influence.

All other parameter dispersions affect the bending moments on both vehicles to a relatively small degree.

Table 1. A Summary of Deviations in Structural Loads Due to +10% Dispersions in Measured Atmospheric Data. Percent Deviations from Nominal for a Sidewind Peaking at 35,000 Feet

Liquid Vehicle				
Deviations / Data Dispersed	Δq (%)	Δα (%)	Δ Bending Moment (%)	ΔRisk of Launch (%)
Air Density	9.34	-1.17	8.0	0.92
Air Temperature	0.08	-0.06	-2.0	-0.26
Wind Velocity	0.05	9.24	8.0	0.92
Wind Shear	0.04	2.38	2.6	0.32
Wind Shear Length	0.05	2.68	2.5	0.32
Solid Vehicle				
Deviations / Data Dispersed	Δq (%)	Δα (%)	Δ Bending Moment (%)	ΔRisk of Launch (%)
Air Density	8.20	-2.07	6.0	0.75
Air Temperature	-0.24	0.09	-0.5	-0.05
Wind Velocity	0.12	2.01	2.2	0.30
Wind Shear	0	7.40	7.3	0.85
Wind Shear Length	0	3.72	3.5	0.45

Effects on Launch Risk

The greatest deviations in launch risk for liquid and solid vehicles are due to dispersions in the same parameters that affect bending moments; that is, air density and wind velocity for the liquid, and air density and wind shear for the solid.

III. METHOD OF ANALYSIS

Nominal Inputs

The method of analysis may be described by first discussing the nominal inputs. Two different types of vehicles were chosen. The first was a small, high velocity, solid-propelled vehicle. The second was a much larger and slower liquid-propelled vehicle. These two vehicles are shown in Figure 1.

The basic trajectories chosen were the mission trajectories for each vehicle. These trajectories differ greatly because of the different missions and the dissimilarities in vehicle configuration and performance.

The basic wind profile was the same for each vehicle to permit the effect of the same dispersions in this wind profile on the response and structural loading of each vehicle to be measured. The basic wind profile chosen is described in Figure 2. The critical wind direction and altitude for the wind peak were determined, and was coincidentally a side wind peaking at 35,000 feet for each vehicle. The wind risk was arbitrarily chosen as the five percent profile. The nominal atmosphere used was the same for both vehicle trajectories to permit the effect of the same dispersion in this atmosphere on the response and structural load of each vehicle to be measured. The nominal atmosphere used was "U.S. Standard Atmosphere, 1962."

Atmospheric Data Dispersions

The atmospheric data that determine the structural loading of a vehicle are air density and air temperature, which are reflected in the nominal atmosphere; and wind velocity, wind shear, and wind shear depth, which are reflected in the basic wind profile. All of the preceding data are coupled in their effects on dynamic pressure and angle of attack. In turn, the rigid body axial load and bending moment on the vehicle structure are primarily direct functions of dynamic pressure and angle of attack. Therefore, by dispersing the preceding atmospheric data, we also vary the loads on the vehicle and

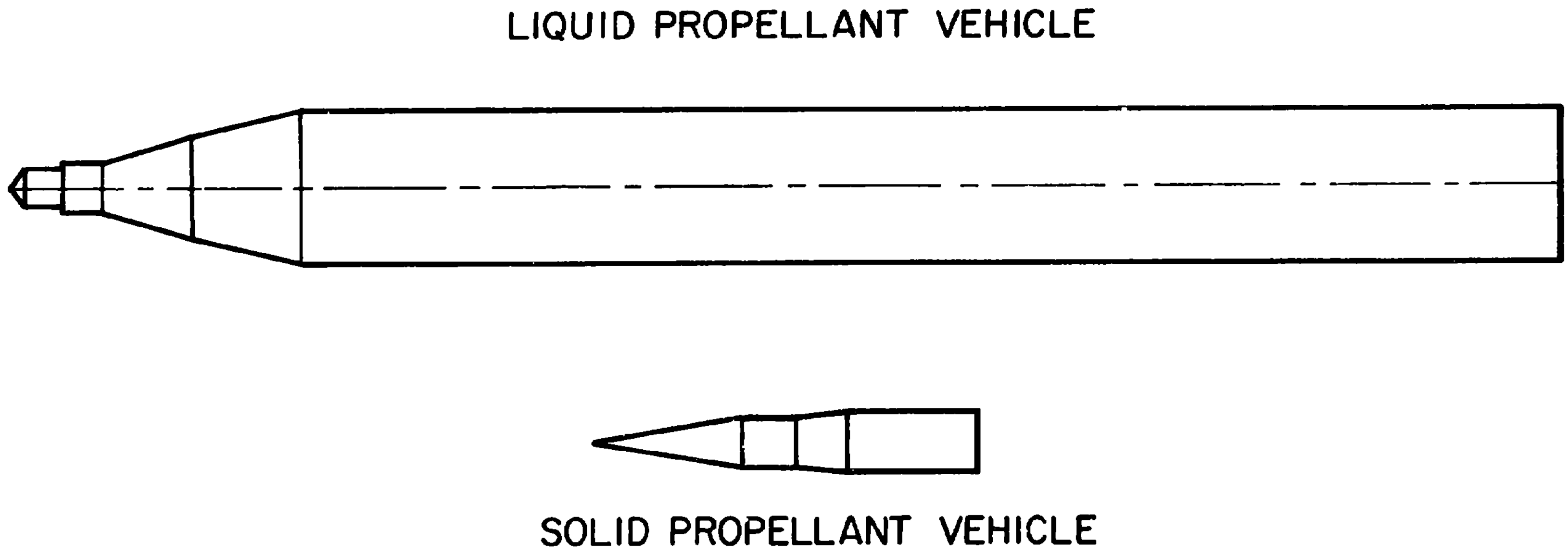

Figure 1. Configurations

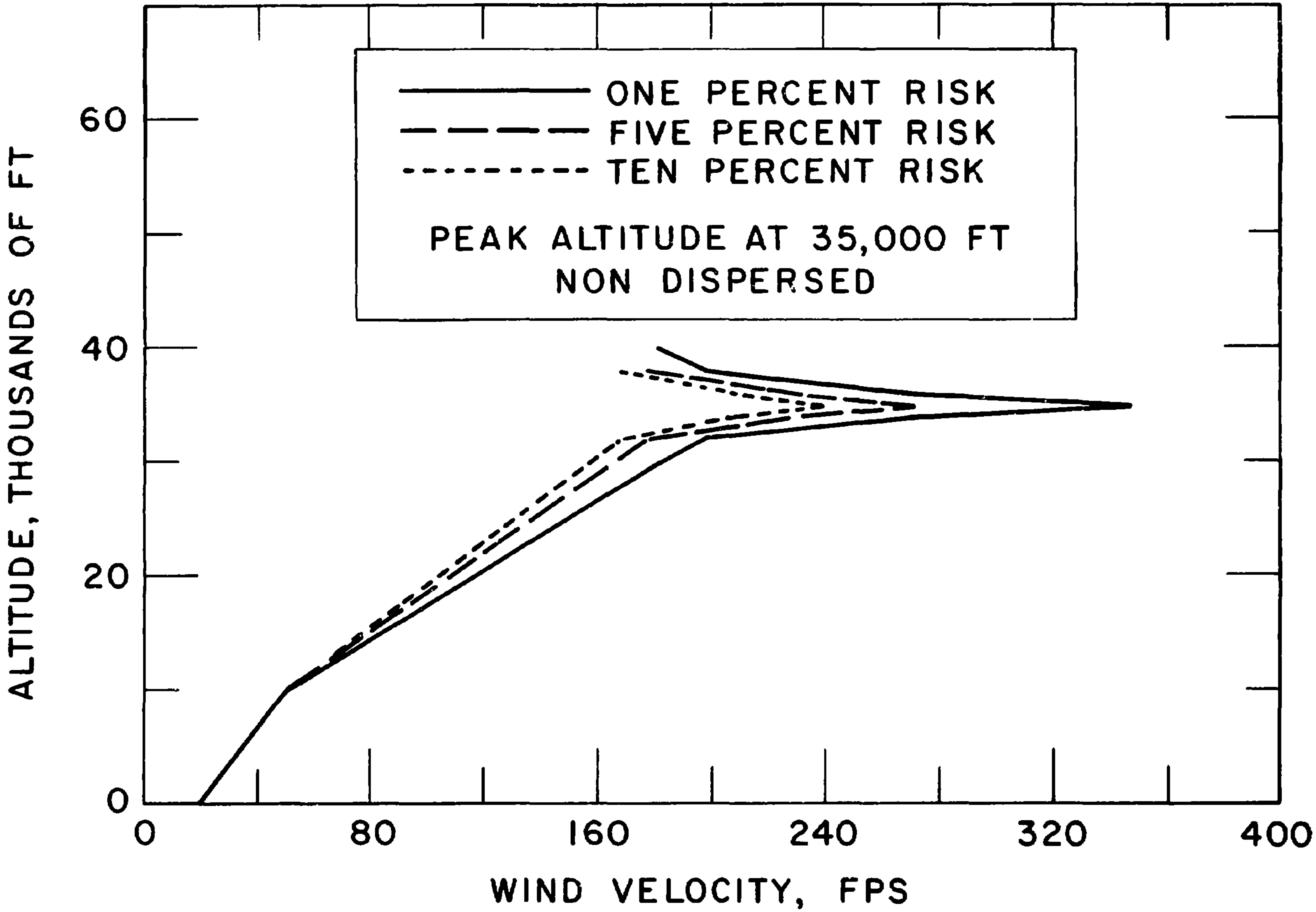

Figure 2. Design Wind Profiles

measure the effect of the dispersion (or simulated inaccuracy in measured data) on the loads.

Six-Degree-of-Freedom Trajectory Simulation

A six-degree-of-freedom trajectory simulation was utilized for each vehicle, inputting the nominal atmospnere, the basic five percent risk side wind profile, and the basic "no-wind" trajectory program for each vehicle. Then a series of trajectories was run for each vehicle, where air density, air temperature, wind velocity, wind shear and wind shear length were dispersed ±5 and ±10 percent, one at a time. These trajectories are listed in Appendix A. The effects of the dispersions on the trajectory were obtained directly from the trajectory simulation.

Six-Degree-of-Freedom Structural Loads Program

The output of the trajectory program was then coupled to a six-degree-of-freedom loads program where the effects on axial load, bending moment, and equivalent axial load were measured. Plots were then made for each vehicle, showing the deviations in load for each dispersion in atmospheric data. The deviation in launch risk from the 5 percent basic wind profile is also shown for each dispersion. This was done by relating changes in structural loading to changes in wind profile risk by running one and ten percent risk wind profiles with no dispersions.

Limitations and Assumptions

Concerning the limitations and assumptions of this study, the loads outputs are entirely rigid body loads; therefore gust and other dynamic effects were not consiaered. However, since rigid body loads are the major portion of total loads and are directly related to the atmospheric data that was dispersed, this omission is justified. Furthermore, the results of the study may not necessarily be applicable directly to all other solid and liquid propelled vehicles, due to differences in nominal trajectories, wind profiles, control systems, configurations, etc.

IV. PRESENTATION OF RESULTS

Several six-degree-of-freedom wind trajectories were simulated for both a solid propellant boosted vehicle and a liquid propellant boosted vehicle.

Load parameters from the dispersed atmospheric wind trajectories were utilized in a computer program to investigate the relative change in load as each atmospheric parameter was dispersed. The results of the investigation are presented in Figures 3 through 13.

Figures 3 and 4 show respectively the percentage change in dynamic pressure and angle-of-attack with respect to the percentage changes in atmospheric data. As would be expected, the atmospheric density has the greater effect on dynamic pressure, while the wind shear and wind velocity have greater effects on the angle-of-attack.

Figure 5 presents the percentage change in equivalent axial load ($P_{EQ} = P_{AXIAL} + 2M/r$) and the corresponding risk wind percent for dispersions on atmospheric density, wind velocity, temperature, wind shear length (scale of distance), and wind shear for both solid propellant and liquid propellant boosted vehicles. In Figure 5 the arrows demonstrate how a percent change in structural load and percent risk wind is determined from a given dispersion in an atmospheric parameter. It should be noted that density, temperature, and wind velocity dispersions produce greater changes in the equivalent axial load for the liquid propellant boosted vehicle than for the solid propellant boosted vehicle, while dispersions on shear and shear length produce the greater changes in load on the solid propellant boosted vehicle. This can also be seen from Figures 3 and 4 since dynamic pressure and angle of attack have a direct effect on the magnitude of the loads. A possible explanation of this phenomena would be that density, temperature, and wind velocity are parameters that directly affect the relative velocity and dynamic pressure of the vehicle; thus, changes in these parameters would affect the slower moving vehicle (in this case the liquid propellant vehicle) more than

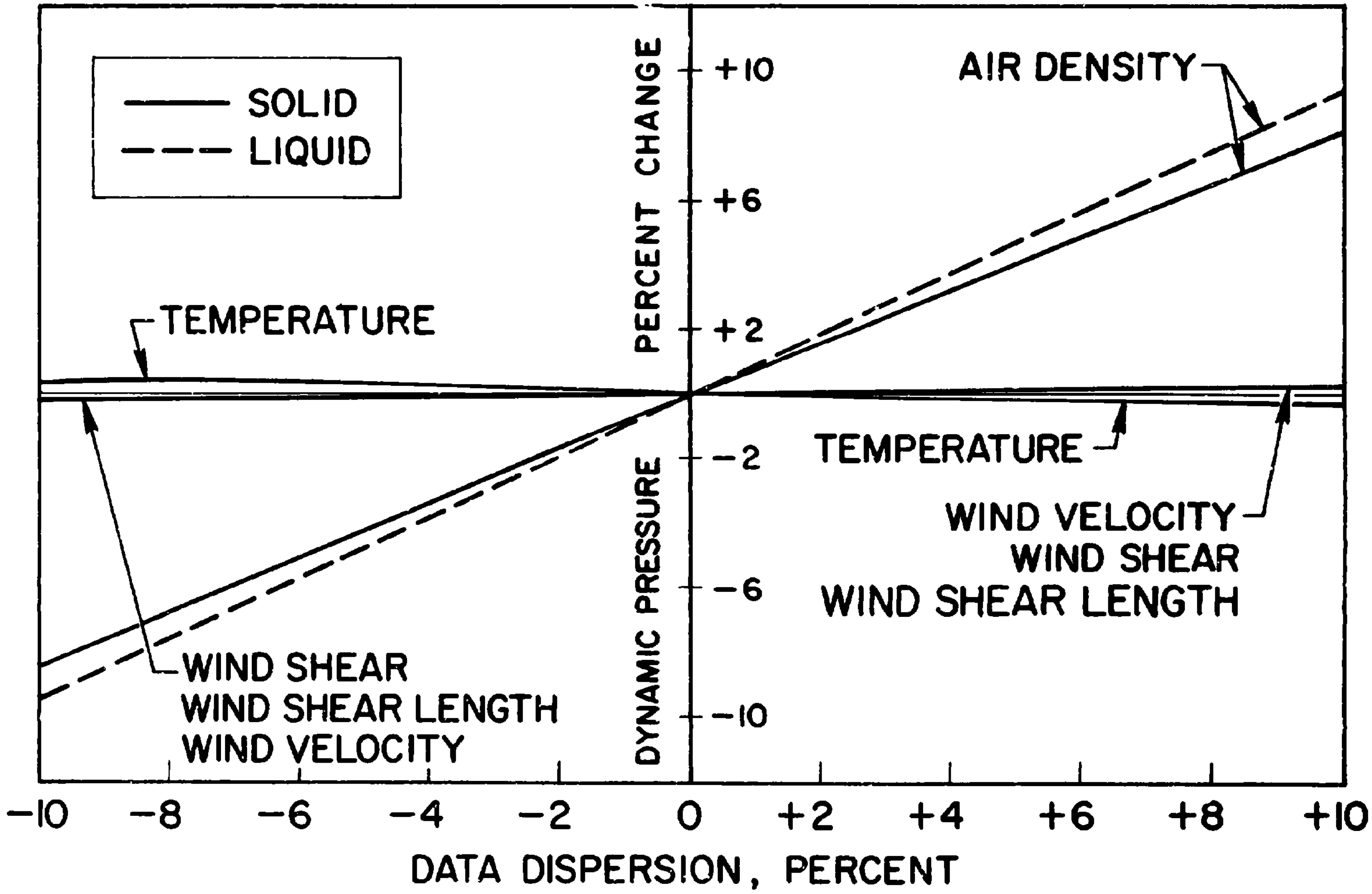

Figure 3. Effects of Dispersions on Dynamic Pressure (q)
Solid and Liquid Propellant Boosters

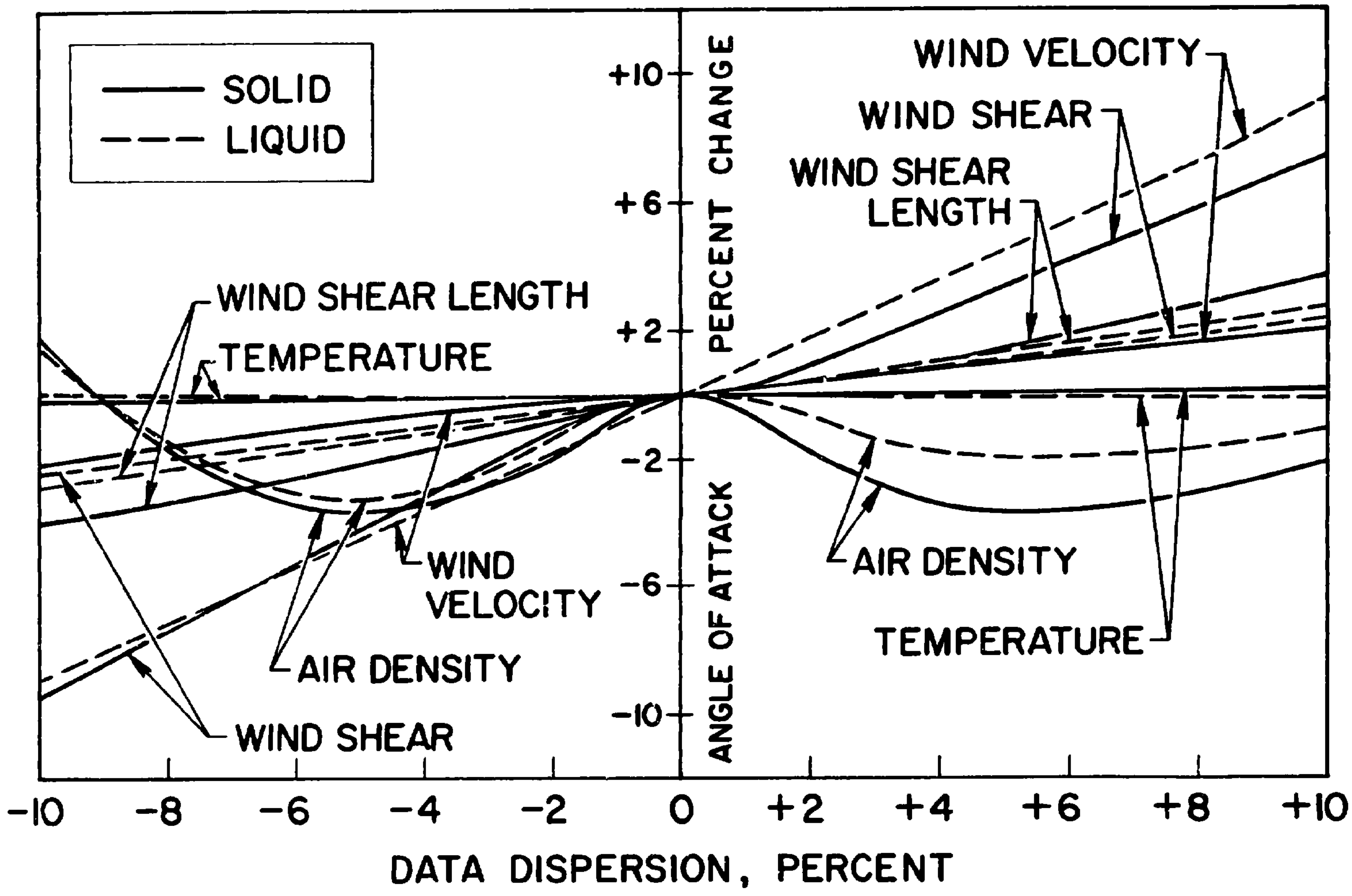

Figure 4. Effects of Dispersions on Angle of Attack (α) Solid and Liquid Propellant Boosters

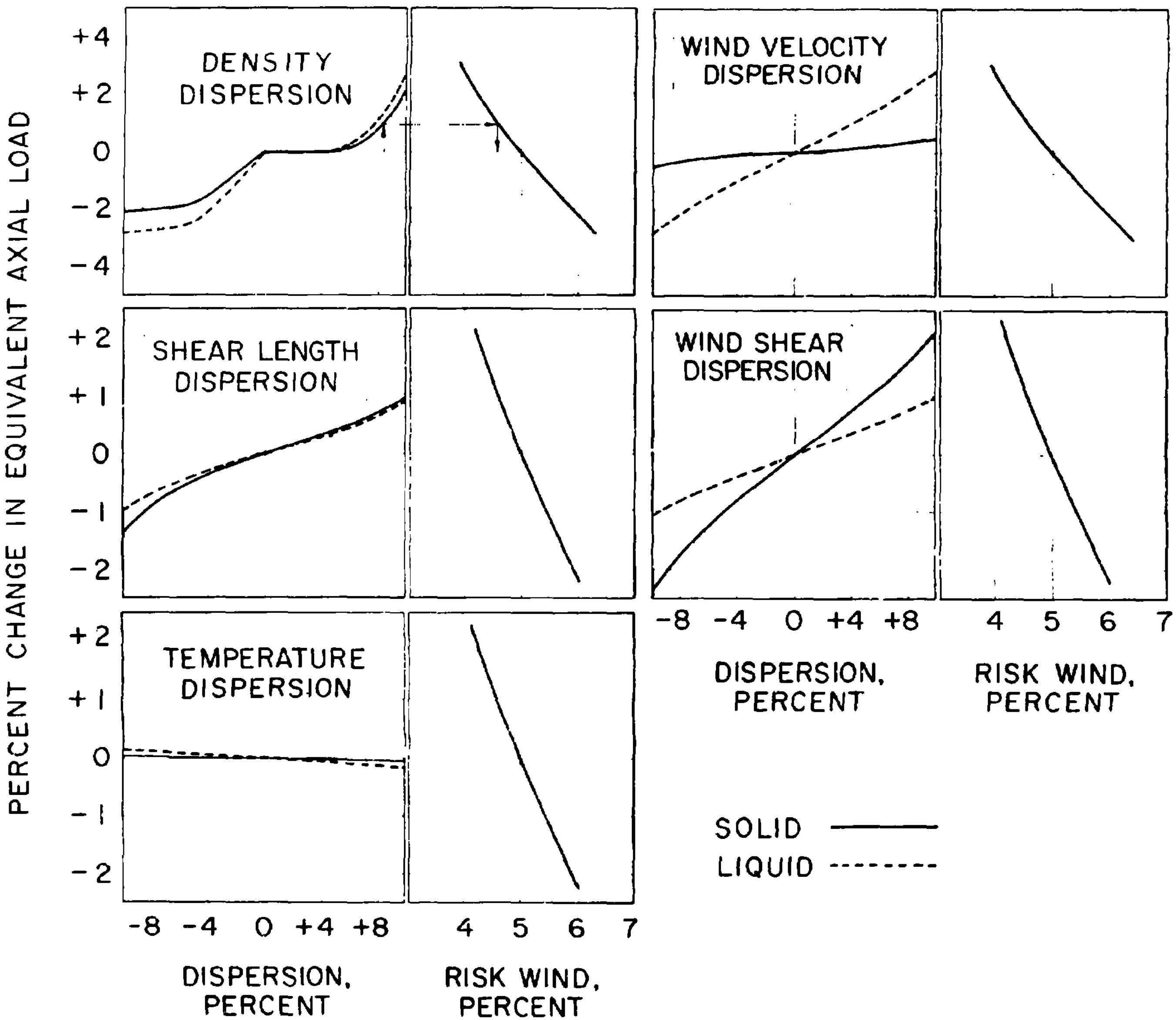

Figure 5. Dispersions, Percent Change in Equivalent Axial Load

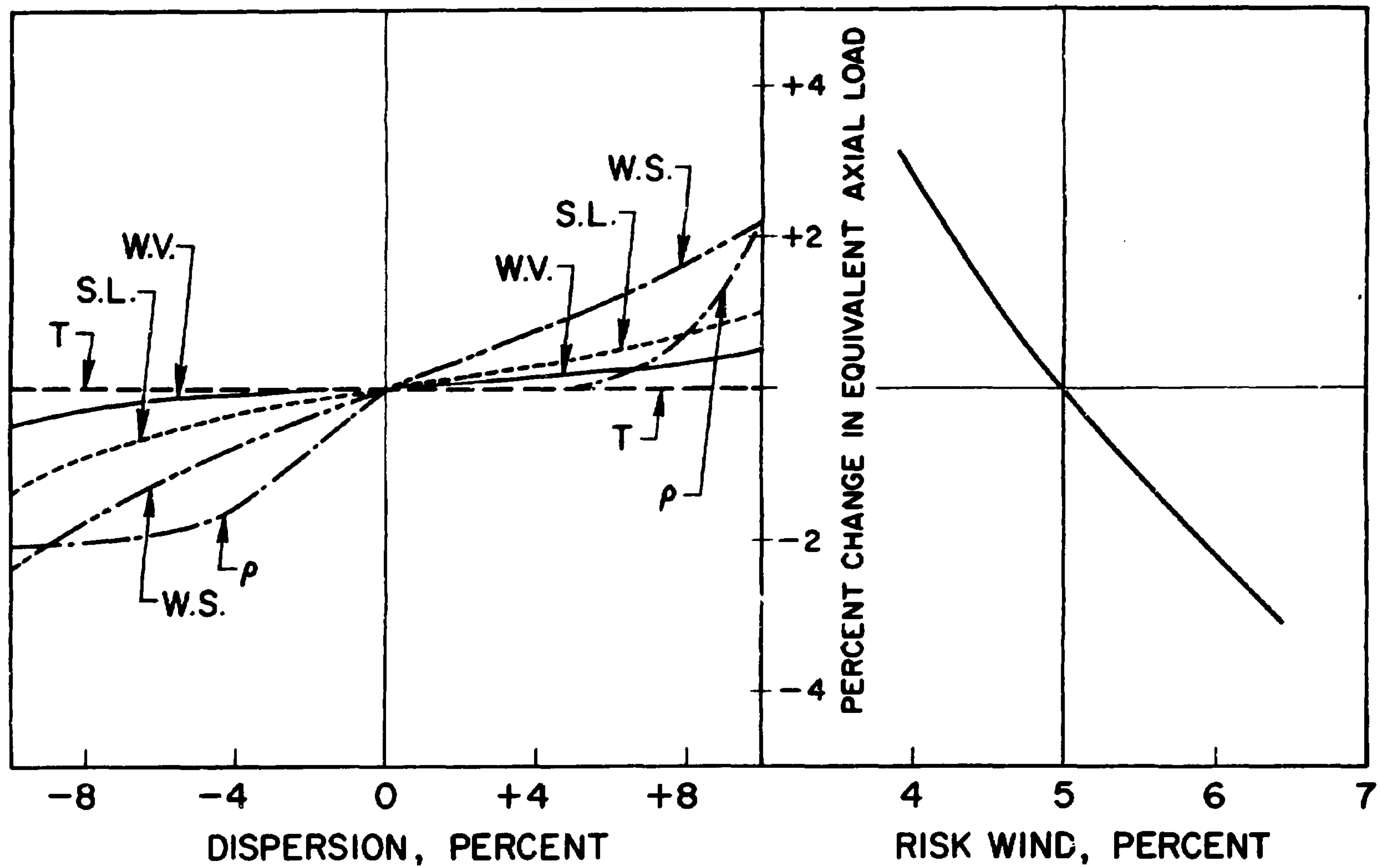

Figure 6. Dispersions, Solid Propellant Booster

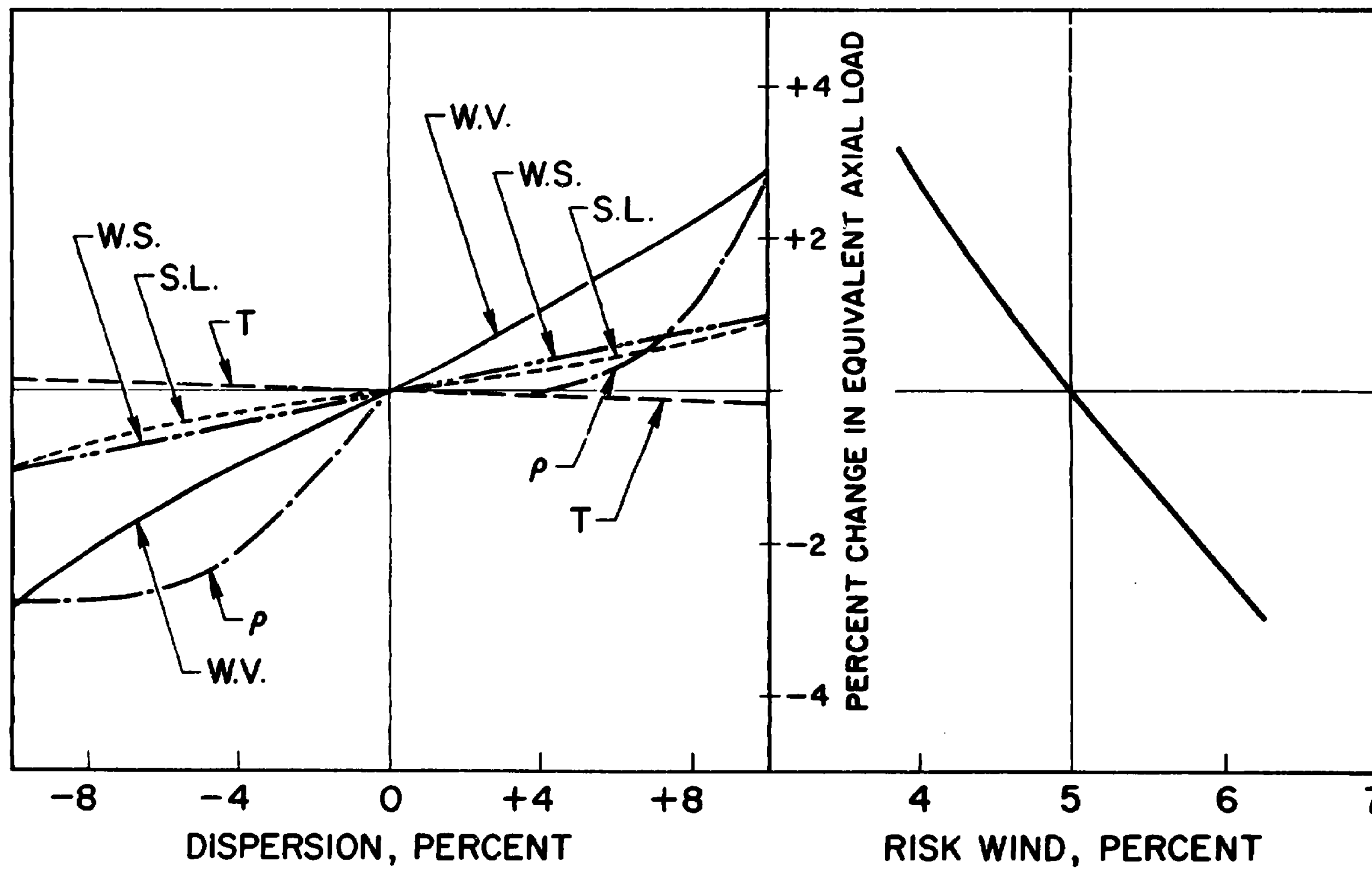

Figure 7. Dispersions, Liquid Propellant Booster

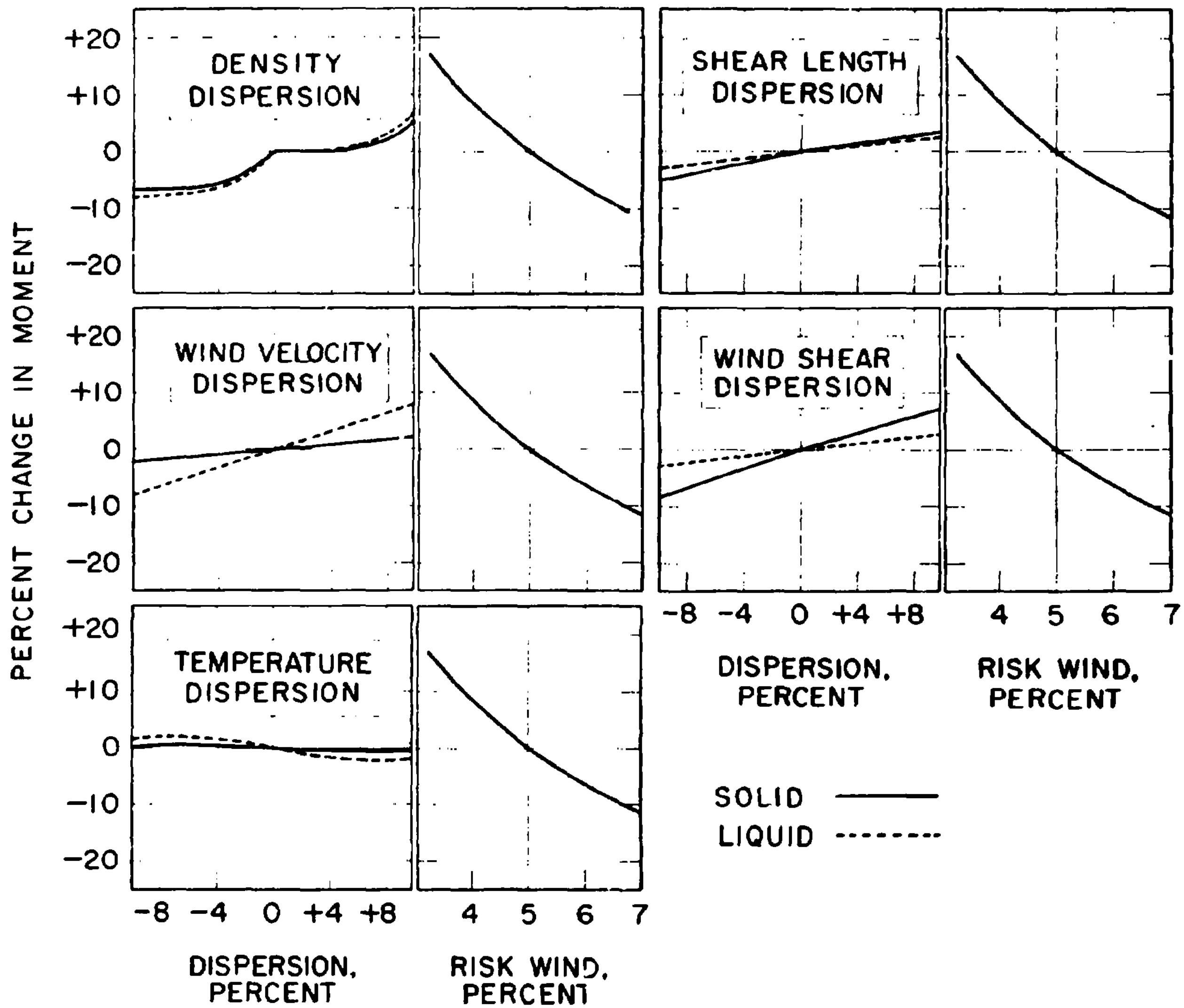

Figure 8. Dispersions, Percent Change in Moment

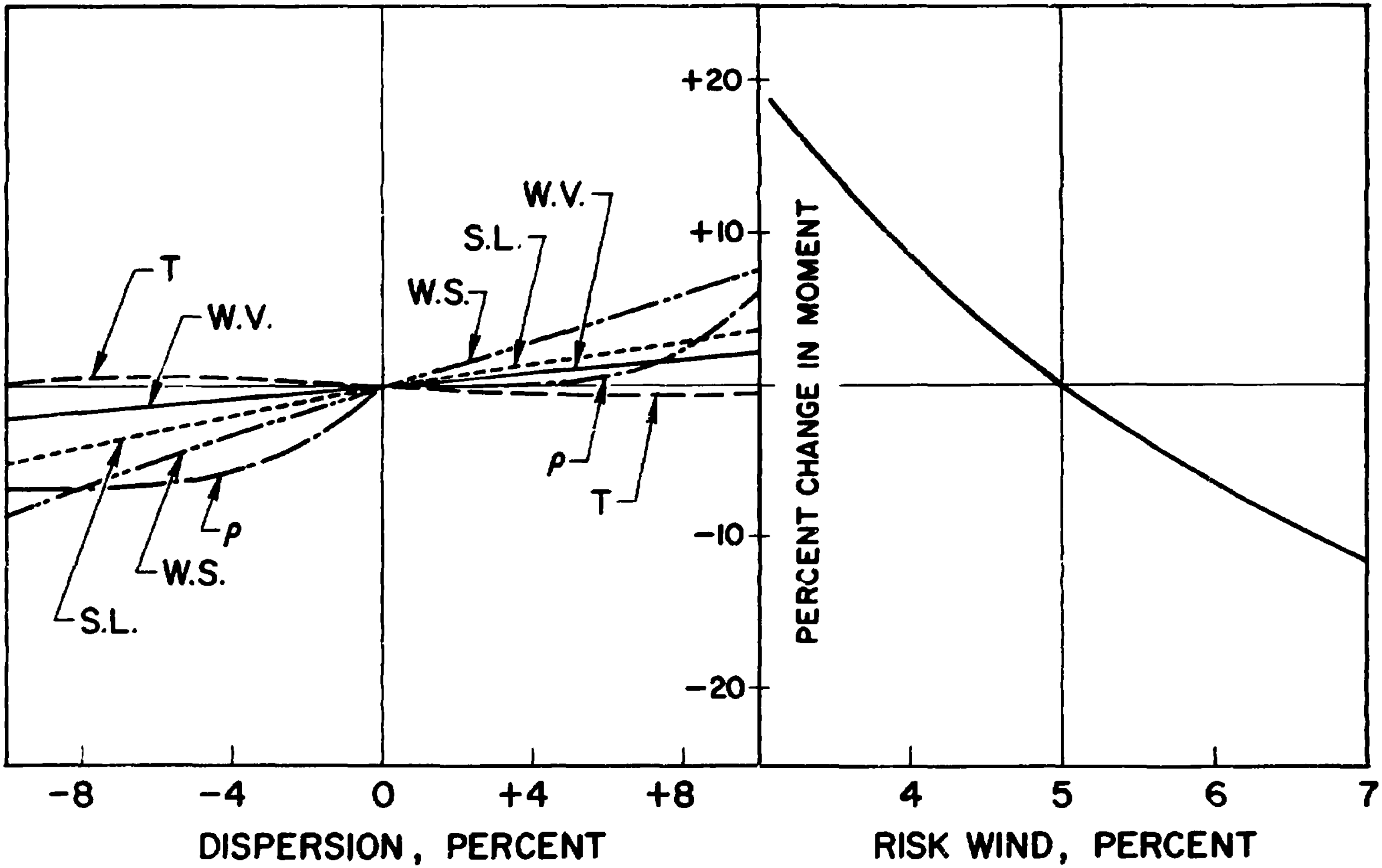

Figure 9. Dispersions, Solid Propellant Booster

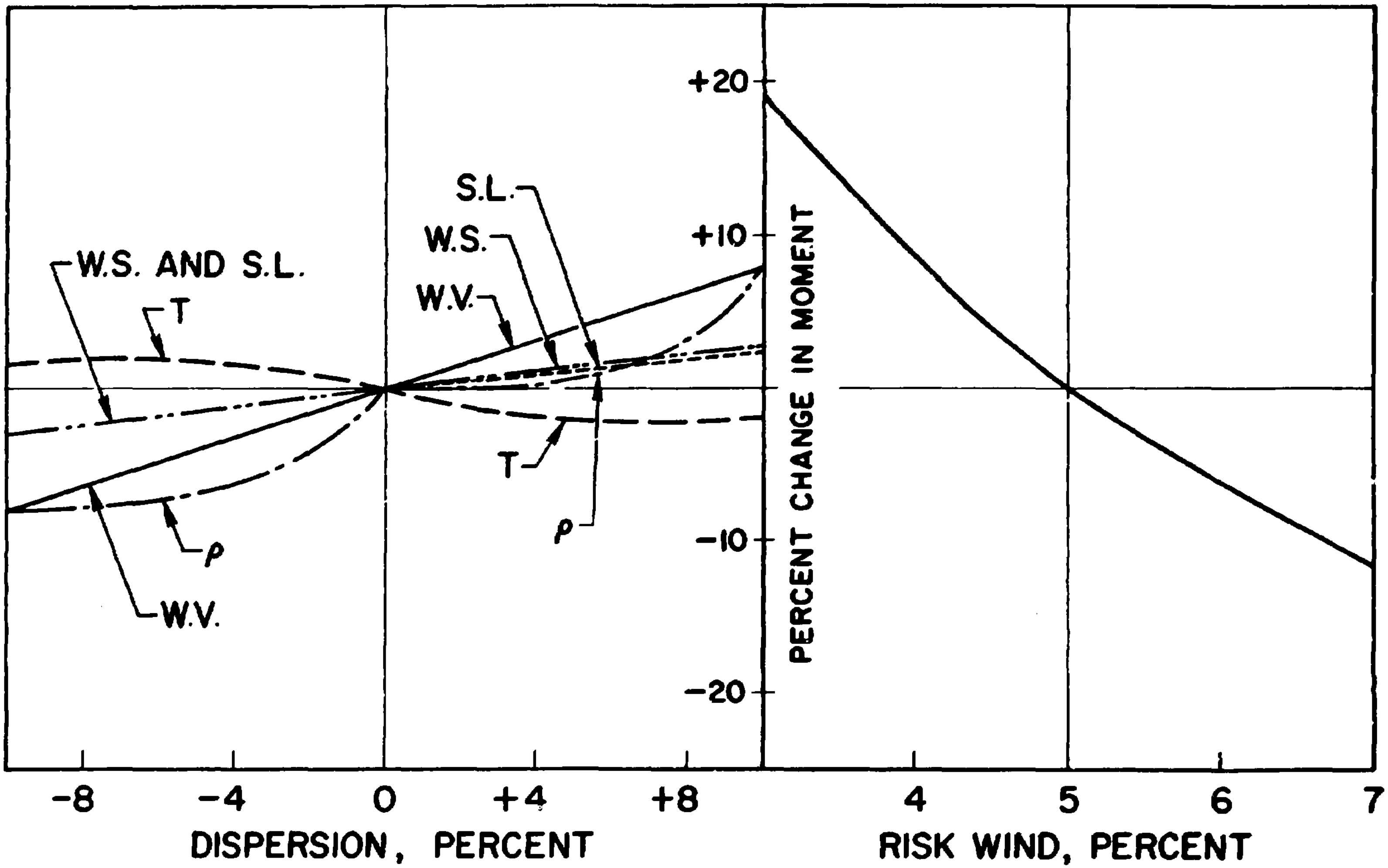

Figure 10. Dispersions, Liquid Propellant Booster

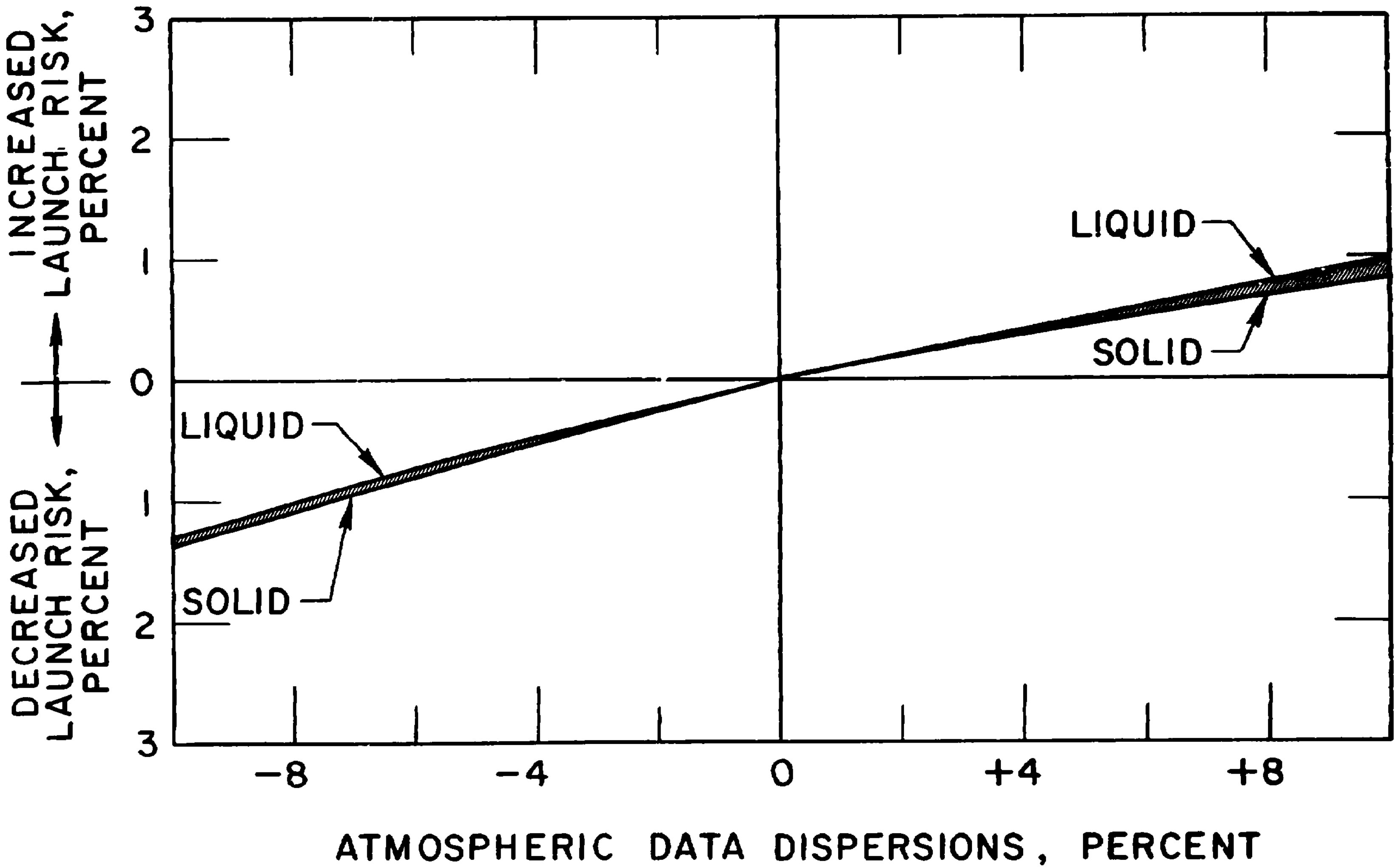

Figure 11 Atmospheric Dispersions vs Deviation in Launch Risk
Solid and Liquid

the faster traveling vehicle. Shear and shear length, however, are parameters which would be more directly related to the control system response; therefore the faster moving vehicle (solid propellant boosted vehicle) would have less time to respond to these changes. This results in greater changes of load on the solid propellant boosted vehicle.

Figures 6 and 7 present the percentage changes in both equivalent axial load and the related risk wind for solid and liquid propellant boosted vehicles, respectively. While Figure 5 shows the relative comparisons between the solid propellant boosted vehicle and the liquid propellant boosted vehicle for each independently dispersed parameter, Figures 6 and 7 show the relative magnitudes of each dispersed parameter for the vehicle investigated.

Figures 8 through 10 present similar illustrations of the percentage change in bending moment as the various atmospheric parameters are dispersed. As would be expected from the relation $P_{EQ} = P_{AXIAL} + 2M/r$, the percent change in bending moment is much greater than the percent change in equivalent axial load. For comparative purposes, Figure 11 shows more directly the change in launch risk for the solid and liquid propellant boosted vehicles as a function of atmospheric dispersions. This figure presents an envelope of maximum effect on launch risk due to all atmospheric parameter dispersions investigated.

V. CONCLUSIONS

This investigation has taken two totally different vehicle configurations to establish the relative percentage changes in the loads and launch risk as a function of errors in measurement of atmospheric data. The study has shown that, although the individually dispersed parameters affected the configurations differently, the envelope of maximum effect on launch risk, as shown in Figure 11, was nearly the same for both the solid and liquid propellant vehicles. Since only two configurations were investigated, it can not be said with confidence that all vehicles would show the same effects experienced by these two vehicles. However, for preliminary design purposes, it is felt that the appropriate figures in this paper, for either a solid or liquid propellant vehicle, may be used to estimate changes in structural load and launch risk due to assumed instrumentation errors.

As previously indicated, the accuracy of atmospheric data measurements does have a noticeable effect on the percentage change in loads and launch risk. The most important parameters were the air density and the wind velocity for the liquid propellant boosted vehicle; and, the air density and wind shear for the solid propellant boosted vehicle. The air density, however, can be measured with an error of less than 0.5% in the altitude range of interest. This, therefore, leaves wind velocity, in the case of the liquid propellant boosted vehicles, and wind shear, in the case of the solid propellant boosted vehicles as the predominant problem areas with regard to accuracy. For example, if 10 percent accuracies on wind shear and wind velocity are the best measurements that can be obtained, a vehicle should be designed for a 4 percent risk criteria rather than a 5 percent risk criteria to account for the data measurement inaccuracies if 5 percent was the original design philosophy.

It would be of interest in future studies to investigate additional vehicle configurations to determine whether they fall in the bandwidth determined by this investigation. Also, additional perturbations such as gust effects may be worth considering in any future investigations. Finally, increased payload weight capability, as a function of the accuracy of atmospheric data measurements, could be investigated as an outcome of this study.

APPENDIX A

TRAJECTORY SIMULATIONS

APPENDIX A. TRAJECTORY SIMULATIONS

Booster	Wind Risk %	Wind Direction	Peak Altitude	Parameter Dispersed	Amt of Dispersion %
Solid	1	Side	34000	None	0
	1	Side	35000	None	0
	1	Side	36000	None	0
	10	Side	35000	None	0
	5	Side	35000	None	0
	5	Side	35000	Density	-10
	5	Side	35000	Density	-5
	5	Side	35000	Density	+5
	5	Side	35000	Density	+10
	5	Side	35000	Temperature	-10
	5	Side	35000	Temperature	-5
	5	Side	35000	Temperature	+5
	5	Side	35000	Temperature	+10
	5	Side	35000	Wind Velocity	-10
	5	Side	35000	Wind Velocity	-5
	5	Side	35000	Wind Velocity	+5
	5	Side	35000	Wind Velocity	+10
	5	Side	35000	Shear	-10
	5	Side	35000	Shear	-5
	5	Side	35000	Shear	+5
	5	Side	35000	Shear	+10
	5	Side	35000	Shear Length	-10
	5	Side	35000	Shear Length	-5
	5	Side	35000	Shear Length	+5
	5	Side	35000	Shear Length	+10
	1	Head	35000	None	0
	1	Head/Side	35000	None	0

APPENDIX A. TRAJECTORY SIMULATIONS (Continued)

Booster	Wind Risk %	Wind Direction	Peak Altitude	Parameter Dispersed	Amt of Dispersion %
Solid	1	Side/Tail	35000	None	0
	1	Tail	35000	None	0
	5	Head	35000	None	0
	5	Head/Side	35000	None	0
	5	Side/Tail	35000	None	0
	5	Tail	35000	None	0
	10	Tail	35000	None	0
	5	Tail	35000	None	0
	5	Tail	35000	Density	-10
	5	Tail	35000	Density	-5
	5	Tail	35000	Density	+5
	5	Tail	35000	Density	+10
	5	Tail	35000	Temperature	-10
	5	Tail	35000	Temperature	-5
	5	Tail	35000	Temperature	+5
	5	Tail	35000	Temperature	+10
	5	Tail	35000	Wind Velocity	-10
	5	Tail	35000	Wind Velocity	-5
	5	Tail	35000	Wind Velocity	+5
	5	Tail	35000	Wind Velocity	+10
	5	Tail	35000	Shear	-10
	5	Tail	35000	Shear	-5
	5	Tail	35000	Shear	+5
	5	Tail	35000	Shear	+10
	5	Tail	35000	Shear Length	-10
	5	Tail	35000	Shear Length	-5
	5	Tail	35000	Shear Length	+5

APPENDIX A. TRAJECTORY SIMULATIONS (Continued)

Booster	Wind Risk %	Wind Direction	Peak Altitude	Parameter Dispersed	Amt of Dispersion %
Solid	5	Tail	35000	Shear Length	+10
Liquid	5	Side	35000	None	0
	10	Side	35000	None	0
	5	Side	35000	Density	-10
	5	Side	35000	Density	+10
	5	Side	35000	Temperature	-10
	5	Side	35000	Temperature	+10
	5	Side	35000	Wind Velocity	-10
	5	Side	35000	Wind Velocity	+10
	5	Side	35000	Shear	-10
	5	Side	35000	Shear	+10
	5	Side	35000	Shear Length	-10
	5	Side	35000	Shear Length	+10

APPENDIX B

WIND CRITERIA

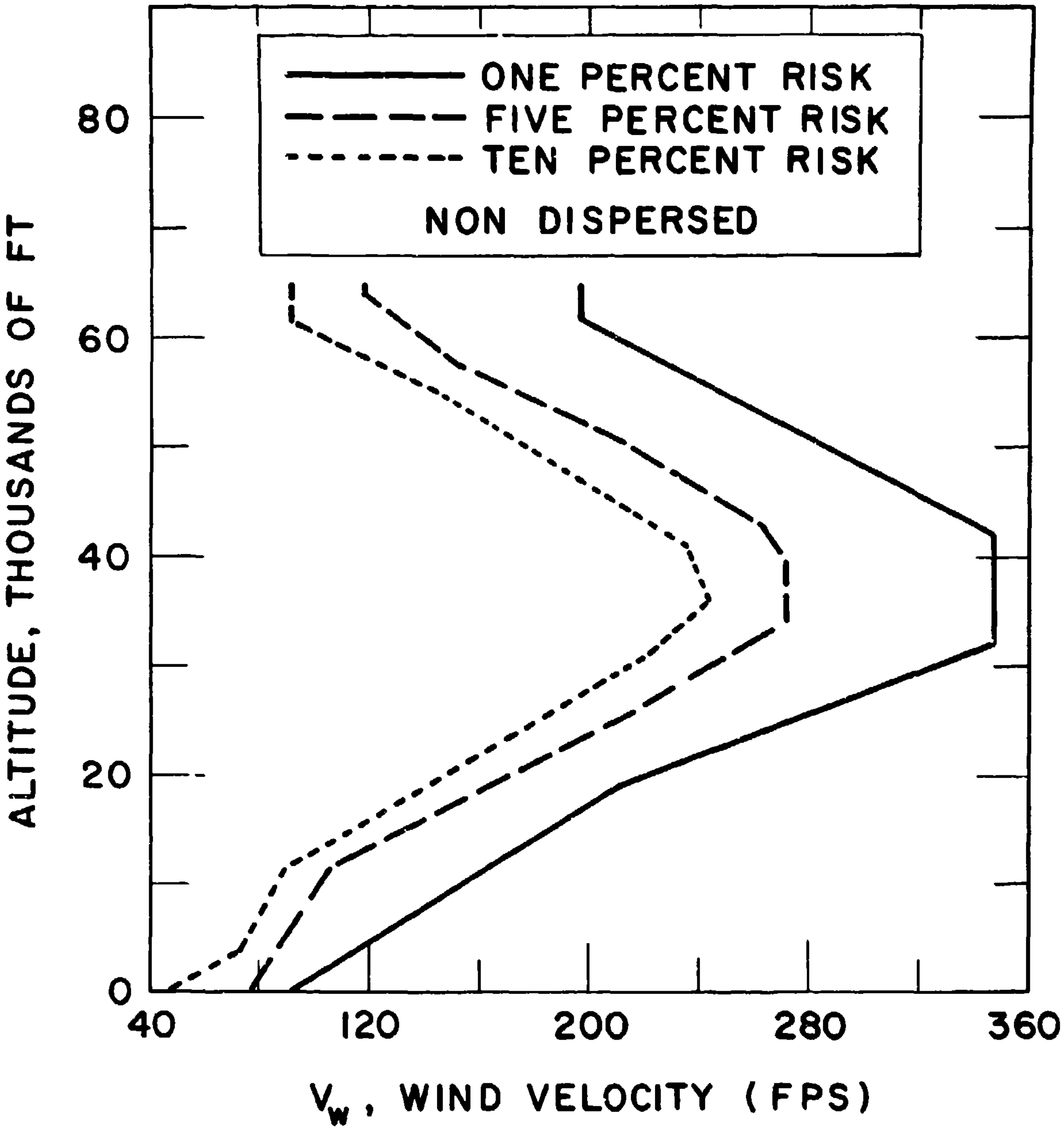

Figure 12. Design Wind Velocity Envelope

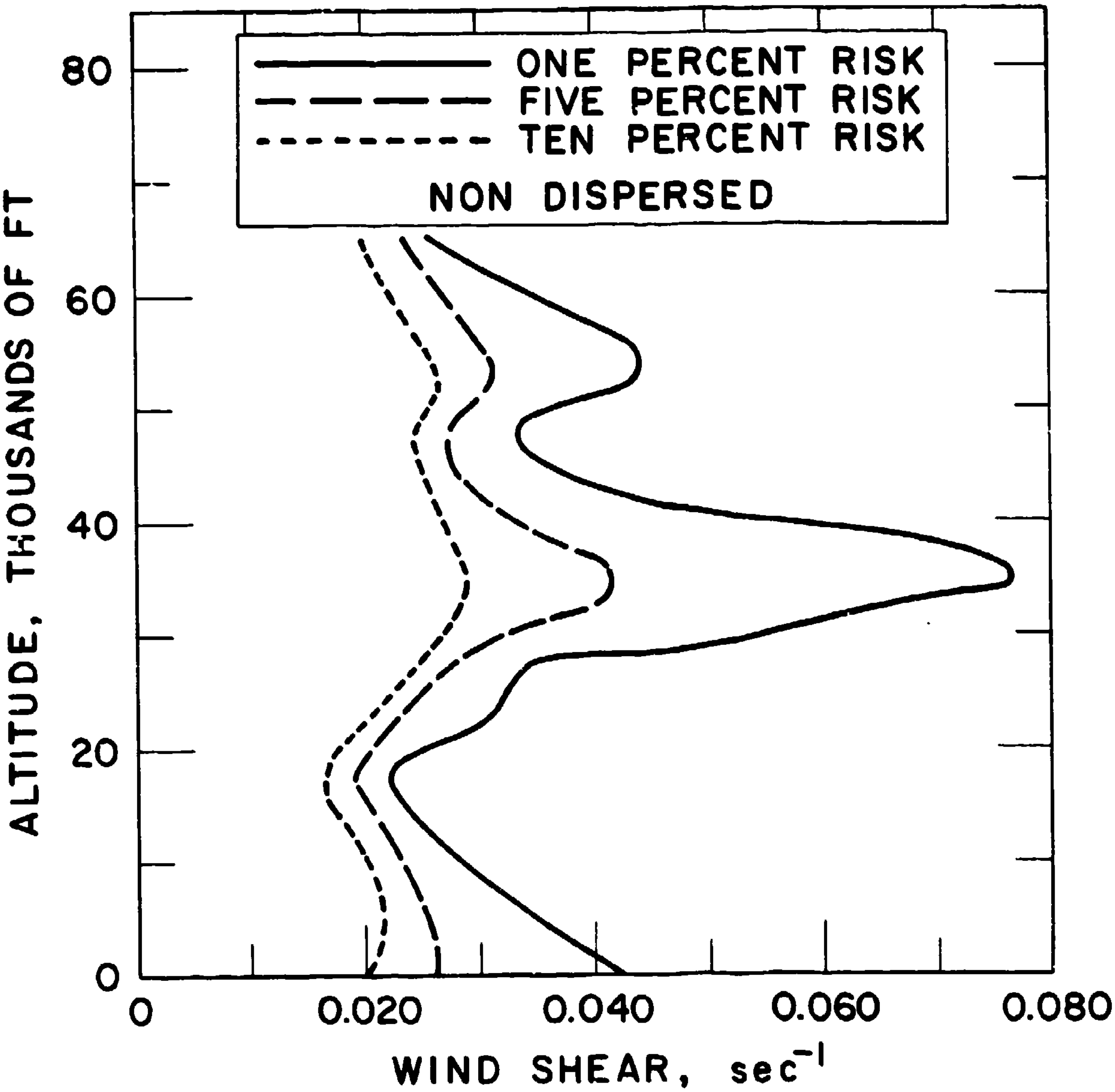

Figure 13. Design Wind Shear Envelope, 1000 Feet Shear Layer

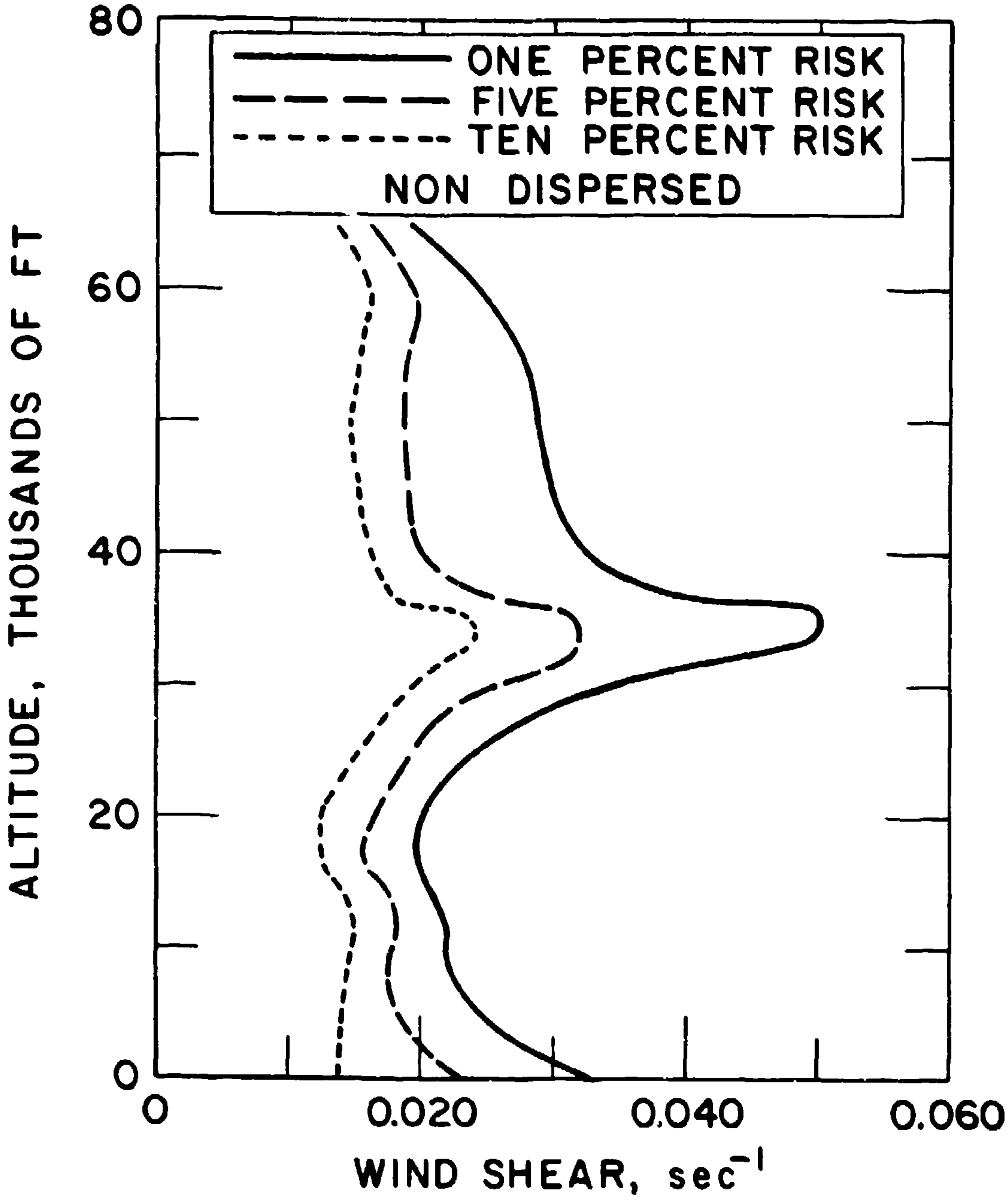

Figure 14. Design Wind Shear Envelope, 3000 Feet Shear Layer

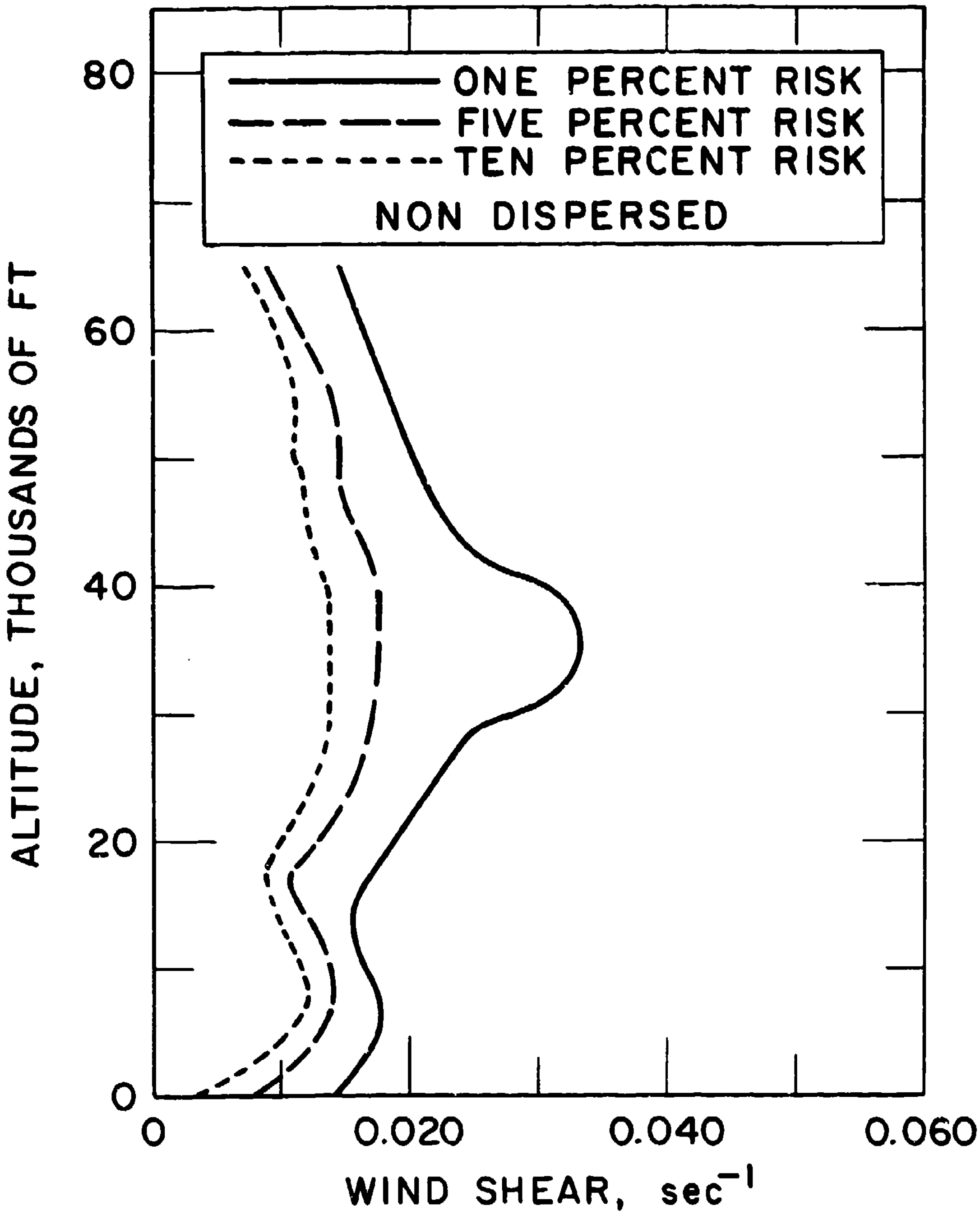

Figure 15. Design Wind Shear Envelope,
5000 Feet Shear Layer

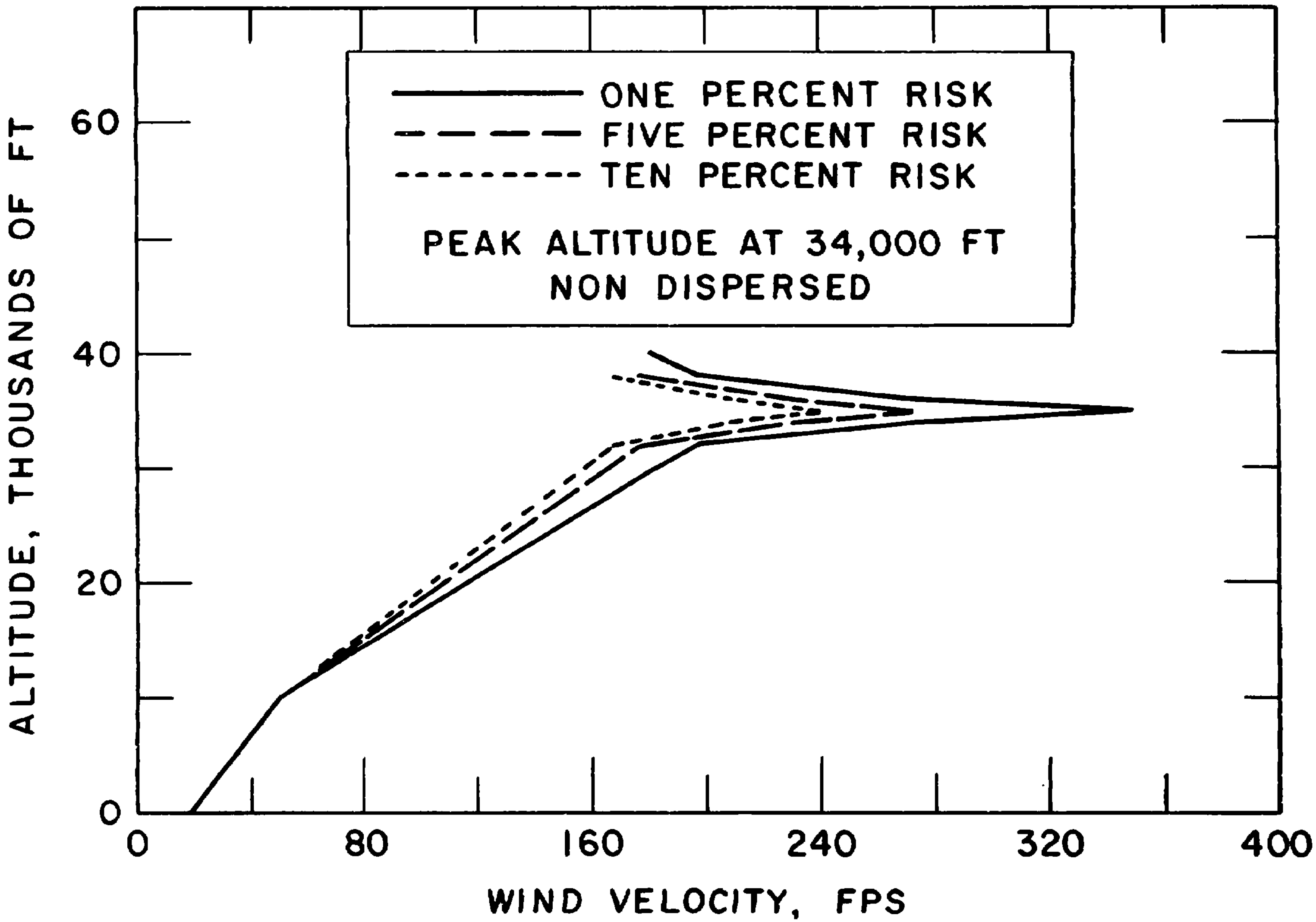

Figure 16. Design Wind Profiles, Peak Altitude at 34,000 Feet

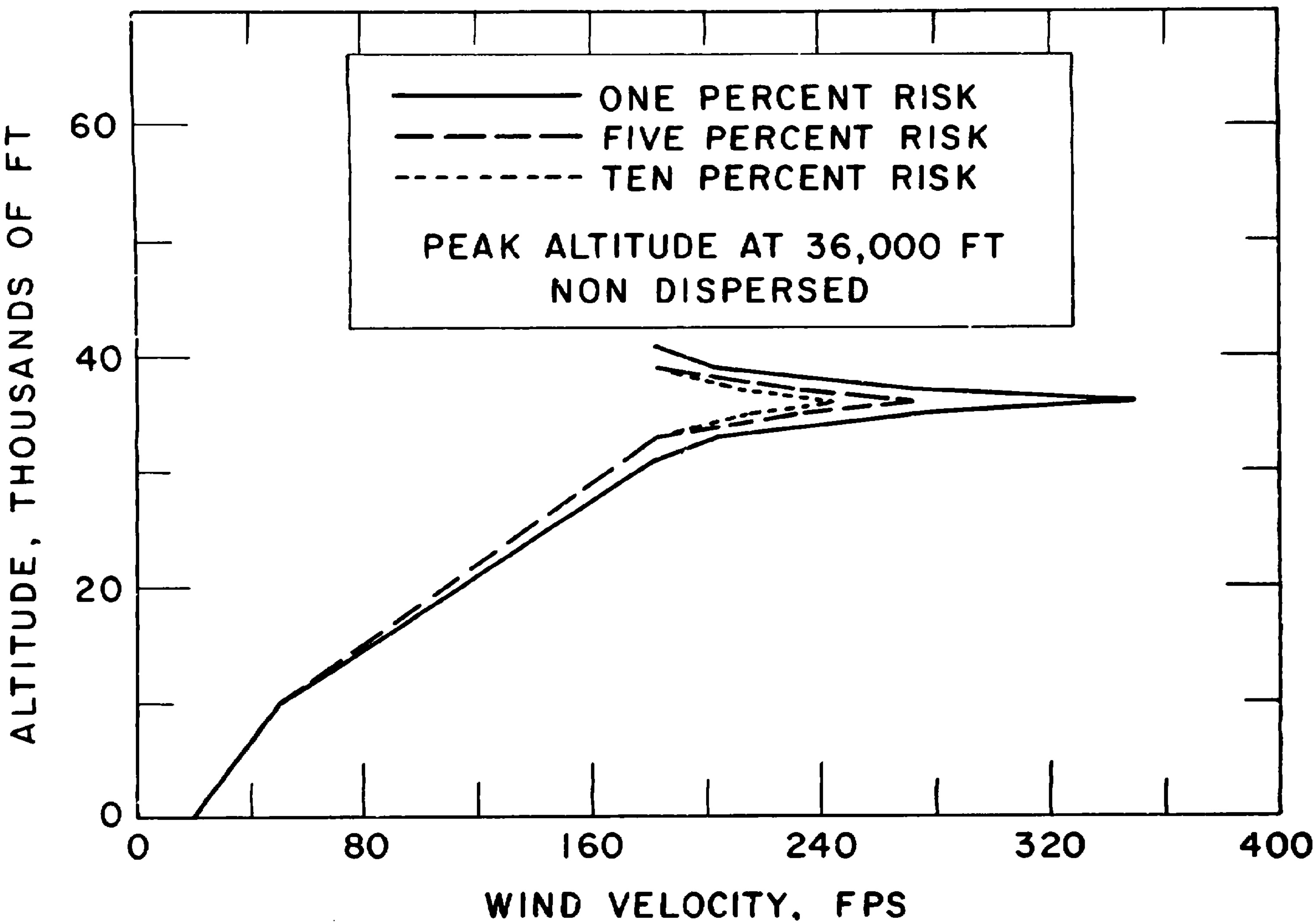

Figure 17. Design Wind Profiles Peak Altitude at 36,000 Feet

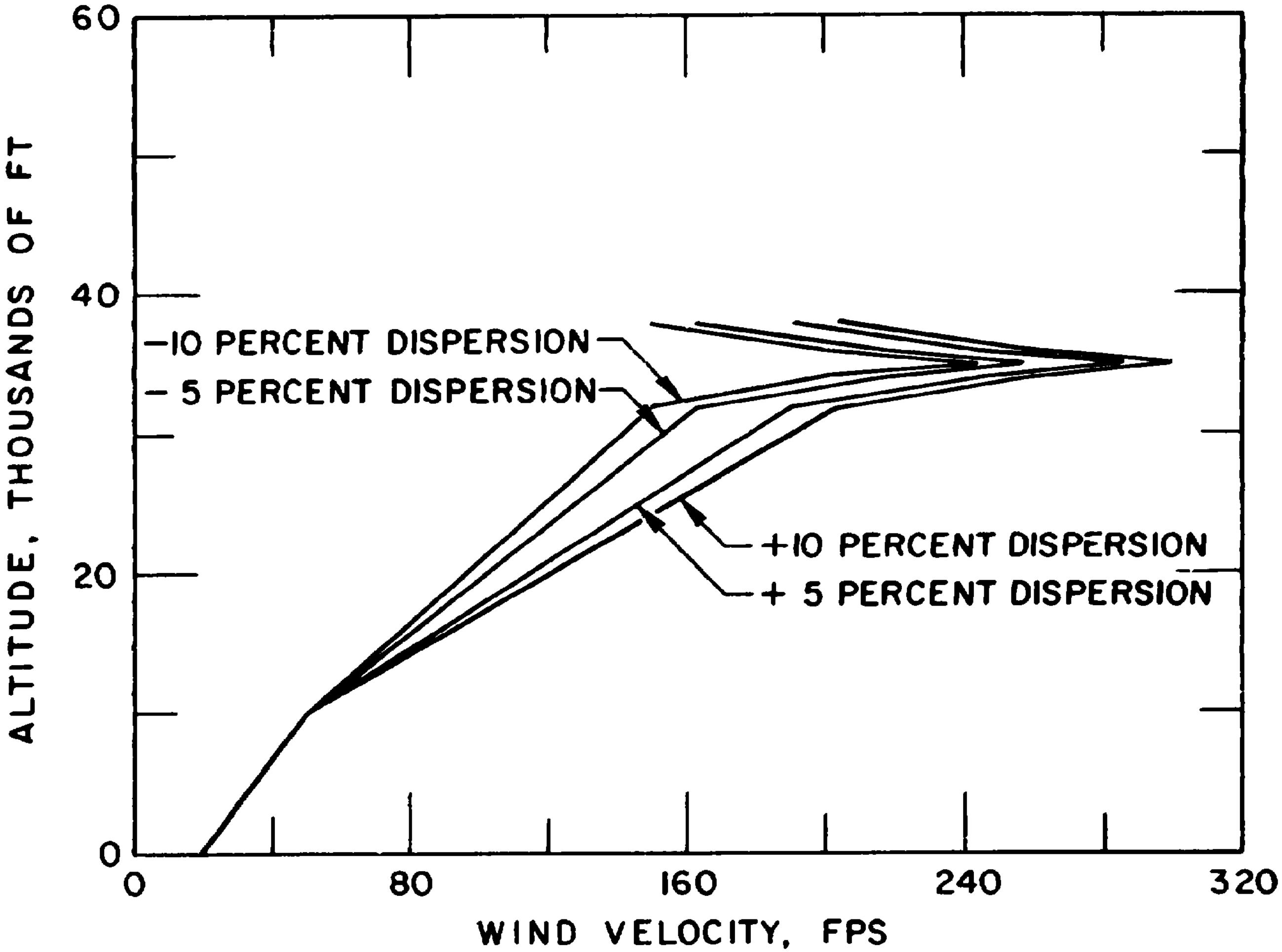

Figure 18. Design Wind Profiles, Wind Velocity Dispersion, Peak Altitude at 35,000 Feet, 5 Percent Risk

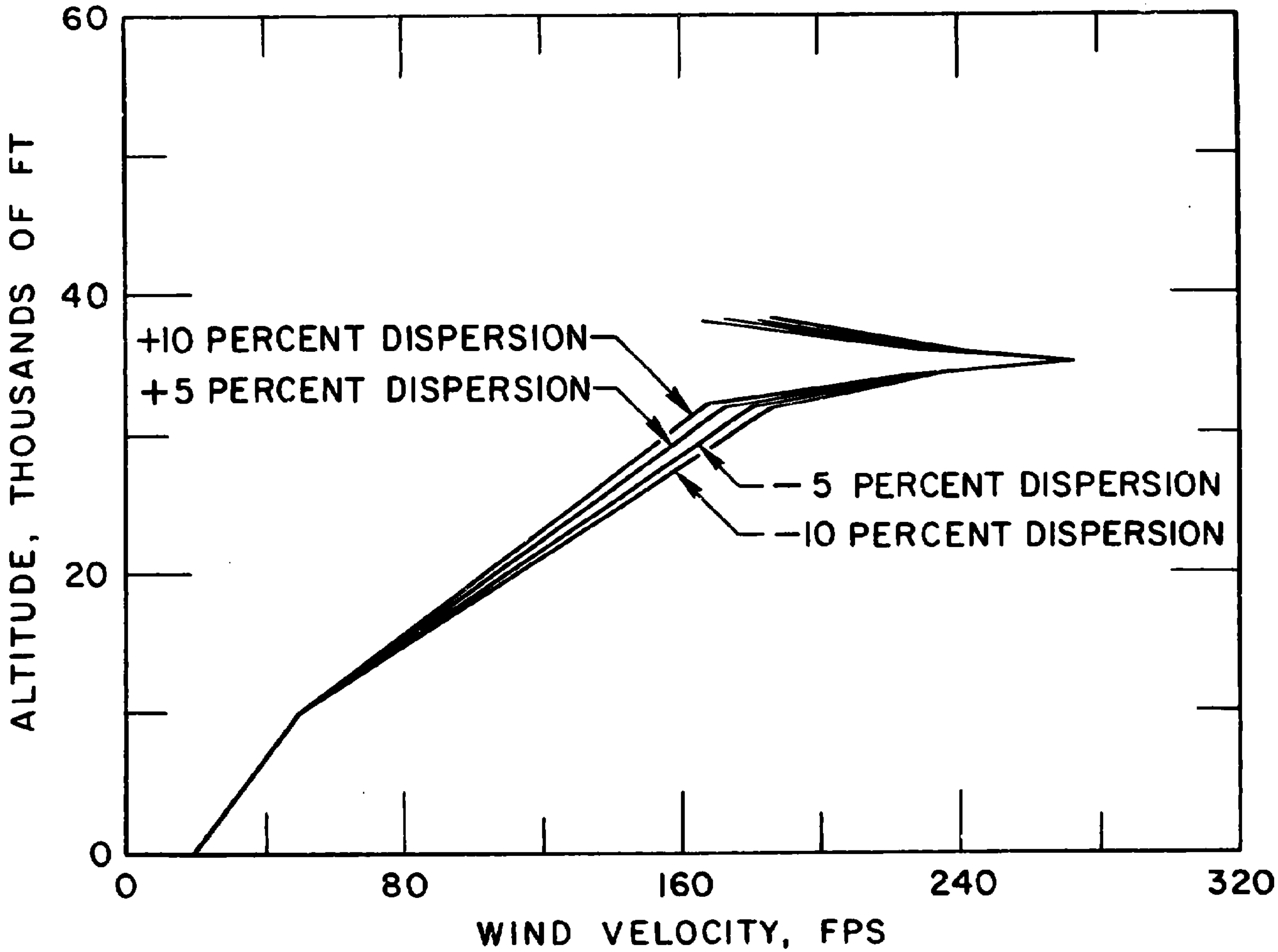

Figure 19. Design Wind Profiles, Wind Shear Dispersion, Peak Altitude at 35,000 Feet, 5 Percent Risk

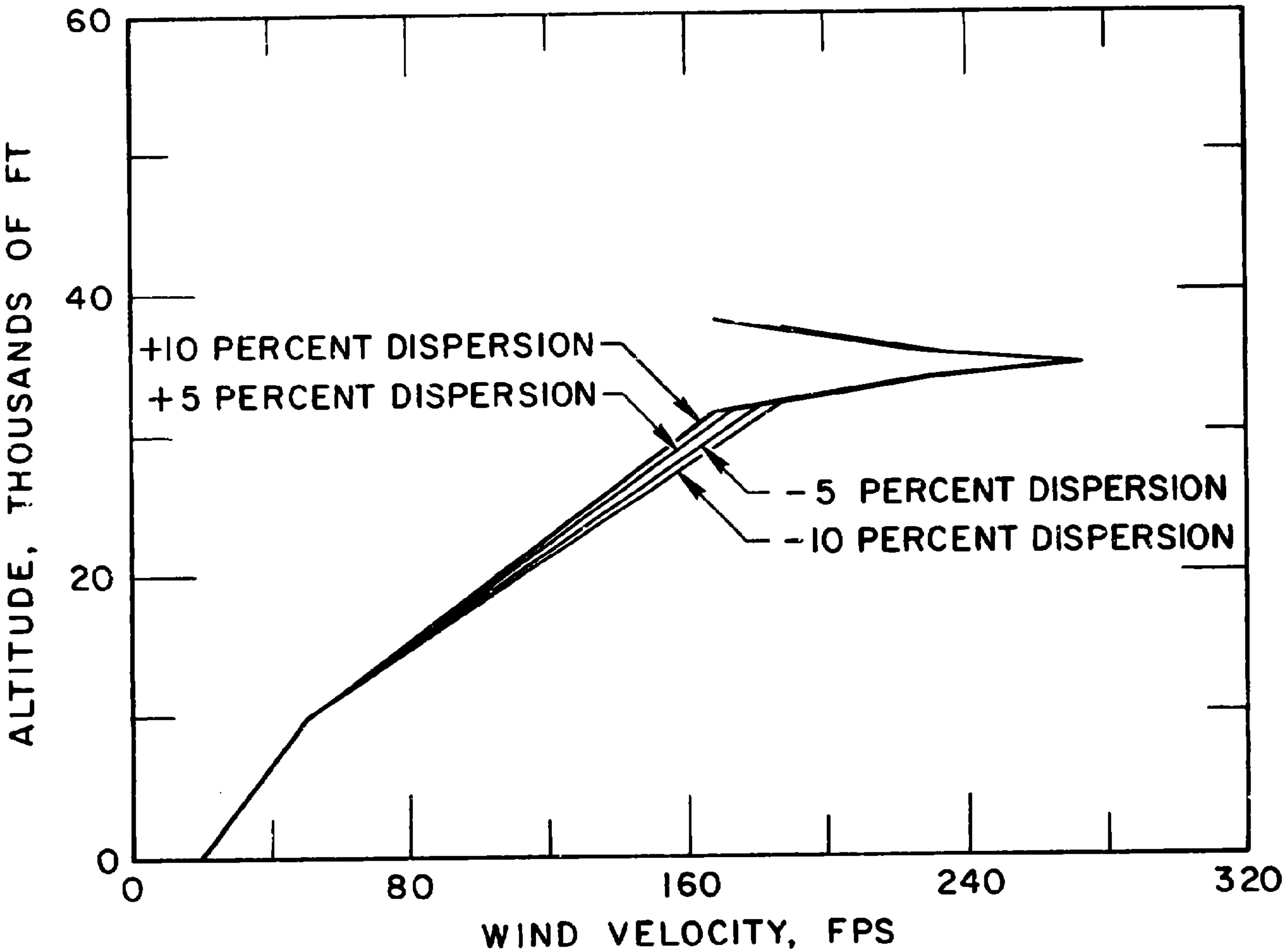

Figure 20. Design Wind Profiles, Shear Length Dispersion, Peak Altitude at 35,000 Feet, 5 Percent Risk

APPENDIX C
TERMS AND SYMBOLS

Air Density - (ρ)

Air Temperature - (T, degress Rankine)

Angle of Attack - (α)

Axial Load - (P_{AXIAL})

Basic Trajectory - the no wind trajectory of the vehicle reflecting non-dispersed inputs such as atmosphere, aerodynamics, weight, etc.

Basic Wind Profile - the wind profile on which dispersions are made.

Bending Moment - (M)

Critical Altitude - that altitude at which the equivalent axial load is a maximum for a particular vehicle station, when the vehicle is flown through a basic trajectory and wind profile.

Dispersions - the perturbations made on the basic wind profile in terms of velocity, wind shear or wind shear length, or to the nominal atmosphere in terms of density or temperature to simulate inaccuracies in data measurements.

Dynamic Pressure - (q)

$$q = \frac{1}{2} \rho v_a^2 \tag{1}$$

Equivalent Axial Load - (P_{EQ})

$$P_{EQ} = P_{AXIAL} + \frac{2M}{r} \tag{2}$$

where

r is radius of vehicle at pertinent station.

Head Wind - a wind blowing from a zero degree azimuth, where the "no wind" velocity of the vehicle is from a 180° azimuth.

Launch Risk - the probability of exceeding a structural load on the vehicle. (This probability is equal to the wind risk used to obtain the loads.)

Nominal Atmosphere - the atmosphere on which dispersions are made.

Relative Air Velocity - (v_a), the velocity of the vehicle center of gravity relative to the air mass.

Side Wind - a wind blowing from a 90^o or 270^o azimuth, where the "no wind" velocity of the vehicle is from a 180^o azimuth.

Tail Wind - a wind blowing from a 180^o azimuth where the "no wind" velocity of the vehicle is from a 180^o azimuth.

Wind Risk - the probability of exceeding a particular wind profile.

Wind Shear - the change in wind velocity over a predetermined altitude band.

Wind Shear Length - the altitude band over which the wind shear is determined.

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